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THE EFFECT OF THE CONDITION OF THE SURFACE LAYERS ON THE CHARACTERISTICS OF THE REFRACTORY ALLOYS EI 437 AND EI 617

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ABSTRACT

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Current knowledge is reviewed concerning the effect of mechanical machining on the characteristics of the E1437 and E1617 nickel-base heat-resistant alloys, designed for the production of turbine blades. Machining tends to cause the hardening of the surface layers, which then differ from the core of the blade. The effect of different machining methods on the condition of the surface layers is compared, and data are included showing these differences as well as changes occurring during the individual steps of the machining process.

Author

Introduction

One of the factors, which has a great influence upon the performance characteristics of turbine blades manufactured from heat-resistant alloys is the condition of the surface layer. The condition of the surface, which is naturally affected by previous machining processes, can be evaluated by the following factors: the amount of internal stress in the surface layer, the depth of the surface layer, the difference between the lattice parameters of the surface layer and those of the core of the blade and the variation in chemical composition. The influence of the surface layers upon the mechanical characteristics has been studied in detail for the common steel alloys, which work under normal temperatures. It was proven without a doubt that surface compressive stresses are very favorable in increasing the limits of fatigue, while on the contrary, a negative relationship of fatigue limits was shown for tensile stresses.

*Numbers in the margin indicate pagination in the original foreign text.

This knowledge is being used in various surface machining processes, namely "milling" and rolling, as well as some heat treatments (surface tempering nitridation), the purpose of which is to bring about favorable compressive stresses in the surface layer, which in return increases the limits of fatigue. Very few such tests have been conducted using heat-resistant alloys and the results have rarely been published. In this paper I would like to present the results of some of the Soviet work which is applicable to this problem and I wish to add the results of our own X-ray measurements of lattice parameters of the surface layer of turbine blades manufactured from the alloy EI 617.

THE DEPENDENCE OF THE MECHANICAL CHARACTERISTICS OF HEAT-RESISTANT ALLOYS UPON THE METHOD OF MACHINING.

A systematic study of the dependence of the mechanical characteristics and condition of the surface has been done by Kishkin and coworkers (ref. 1). Based on standard samples which were treated according to the previously established variables of the operation, the amount of internal stress and the depth of surface layer effected by the machining was established. The internal stress was determined by mechanical measurement, namely the tangential stress from the apparent deformation, the axial stress from the bending of the horizontal slave after the skin layer has been etched away. The depth of the layer effected by the mechanical machining was established by measuring of the microhardness on oblique cuts in the horizontal board. At the same time, test rods were treated in the same way for experiments to determine their mechanical characteristics. Next to the short-term mechanical characteristics (tensile tests) the long-lasting characteristics were found as well: strength during creep, the limits of fatigue at normal temperature, at 700°C, and the thermal fatigue. In addition, the characteristic results of these tests will be shown.

The relative effect of hardening of the surface layer on the short-term characteristics of alloyEI 437A at various testing temperatures.

TABLE 1

Method of surface machining	20 °C			700 °C			800 °C		
	σ_{p_t} kp/mm^2	δ %	Ψ %	σ_{p_t} kp/mm^2	δ %	Ψ %	σ_{p_t} kp/mm^2	δ %	Ψ %
lathe tooling + final electro-lytical polishing	120.7	34.6	42.4	86.8	10.8	13.4	62.2	13.2	17.2
lathe tooling (machining) as final process	115.0	31.6	35.7	83.3	7.6	11.3	64.7	13.2	19.7
grinding	117.0	34.6	35.9	88.2	13.6	18.5	63.2	2.0	23.5
grinding after previous lathe tooling	119.4	31.2	36.0	92.6	12.4	16.0	64.7	14.8	22.3
polishing after previous grinding	120.0	28.8	38.6	91.3	13.2	16.9	65.0	15.8	25.2
milling	121.9 118.0	31.0 37.4	22.5 33.6	83.4 80.9	5.0 7.2	7.8 18.6	56.4 56.8	4.8 9.6	7.3 23.3

From Table 1 it becomes apparent that the method of machining has no substantial effect on the short-term strength characteristics of the alloy. /46

Longlasting strength during (flotation).

By long-term tests the substantial effects of machining operation come into being.

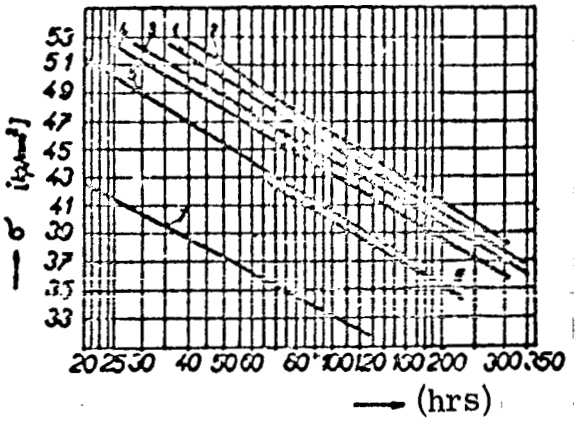

Figure 1. The Influence of Hardening on the Limits of Long-lasting Strength Resulting from Various Machining Methods; Test Temperature 700°C.

1. electrolytical polishing (without hardening)
2. polishing after grinding
3. polishing after surface lathe tooling
4. grinding
5. lathe surface tooling (lathe machining)
6. milling
7. rolling

The influence on the limit of strength during (flotation) is pictured in Figure 1 and in Table 2.

TABLE 2

Method of surface machining	Depth of hardening of layer (μ)	700 °C $\sigma_{t_p}100$ (kp/mm^2)	800 °C $\sigma_{t_p}100$ (kp/mm^2)
electrolytical polishing (the hardened layer was removed)	-	45.2	20.4
grinding	49.7	44.3	20.0
polishing after lathe tooling	75.9	43.2	19.5
lathe tooling (lathe machining)	128.2	-	16.5
milling	149.8	40.0	17.4
rolling	296.8	33.0	11.3

Fatigue

The results of the fatigue tests are noted in Table 3. Tested were smooth rods of 7.52mm diameter at bending, during rotation at stress load (loading) of $\sigma = 42$ kp/mm^2.

Thermal Fatigue

The tests for thermal fatigue were held in two different environments; duration of each cycle was 1 hour.

Environ I.

heating at the stress load $\sigma = 35$ kp/mm^2
from 350°C to 700°C . . . . . 5 minutes

creep at 700°C . . . . . 50 minutes

cooling to 350°C . . . . . 5 minutes

Environ II.

heating at the pressure $\sigma = 18$ kp/mm^2
from 350°C to 800°C . . . . . 5 minutes

creep at 800°C . . . . . 50 minutes

cooling to 350°C . . . . . 5 minutes

The results of the tests are included in Table 4.

From the test results is evident the negative effect of hardening of surface layers on the resistance to thermal fatigue. The results show, that even the compressive stresses brought about by milling and rolling, which normally have a positive effect on the limits of fatigue are substantially negated in tests results when compared with the samples which had their hardened surface layer removed by electrolytical polishing.

The measuring was done on samples of standard shapes. Added are measurements of samples which were cut out of turbine blades mechanically treated by various methods: (ref. 2).

I. grinding

II. grinding + etching + grinding (controllable category, gradual grinding, low speed).

III. variable II. + heating (sintering?) at 950°C, 2 hours, cooling at the room temperature.

IV. lathe tooling, grinding, polishing.

V. Variable IV + heating (sintering) at 950°C, 2 hours, cooling at the room temperature.

The samples were taken from the areas of blades most susceptible to development of flaws after a short time of running.

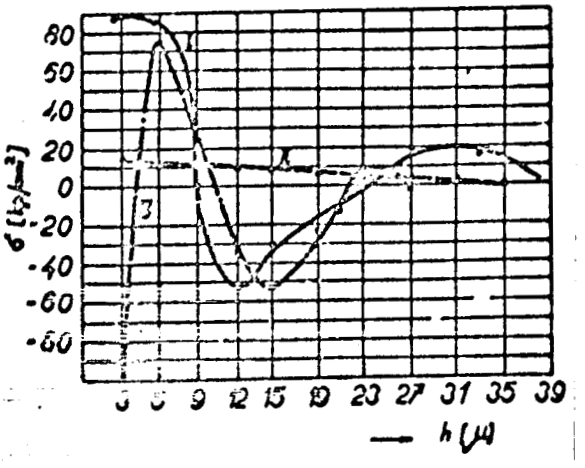

Figure 2. Distribution of Remaining Stresses in the Surface Layer of the Blade Pins, which were Machined According to the Variables I, II, IV.

The distribution of the residual stresses in the surface layer of the blade pins is pictured in Figure 2. After grinding, the tensile stresses remain on the surface. After polishing, the compressive stresses remain. The favorable course of stresses in the variable II. was achieved by removing the deformed layers through etching and final light grinding. The samples, which were taken from the turbine blades after heat treating (sintering), had practically

TABLE 3

Method of surface machining	Depth of hardening of the layer μ	Residual stresses σ_τ kp/mm^2	Residual stresses σ_o kp/mm^2	Number of cycles till cessation of stress loads σ = 42kp/mm^2			
electrolytical polishing (removing of the hardened layer)	-	-	-	4 850 000	-	13 481 000	-
lathe tooling	128.4	50	20	2 850 000	41.2	9 017 600	33.7
grinding	49.7	52	15	3 613 400	25.6	11 731 200	13.4
polishing after lathe tooling	75.9	55	-30	4 289 000	11.6	10 036 000	26.0
polishing after grinding	37.9	50	-25	5 034 300	increase 3.7	12 672 000	6.0
rolling	296.8	-90	-185	7 853 000	increase 61.4	14 385 200	increase 6.4
milling process	189.2	-80	-55	16 810 000	increase 246	15 235 100	increase 12.6

no residual stresses. Figure 3 reflects characteristic comparison of conditions before and after the heating (sintering).

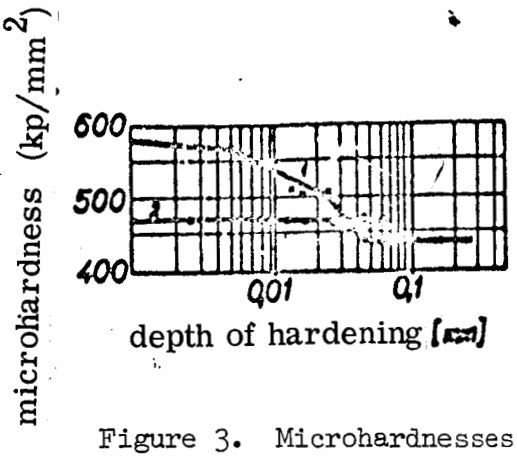

Figure 3. Microhardnesses of the Surface of the Blade.

1. After polishing
2. After polishing and heating (sintering) for the purpose of removing stress.

The results confirmed the expected favorable influence of compressive residual stresses caused by milling process on the limit of fatigue under normal temperature; at temperatures of 700°C the effects do not show up appreciably.

TABLE 4.

Method of Surface Machining	700°C, σ = 35 kp/mm²			800°C, σ = 18 kp/mm²		
	Time Till Cessation of Load Stress in hrs.	δ %	ψ %	Time Till Cessation of Load Stress in hrs.	δ %	ψ %
electrolytical polishing	234	1.2	3.1	79	5.5	8.5
lathe tooling	129	1.1	2.8	57	2.0	3.5
grinding	171	2.0	3.4	69	3.2	4.5
polishing after lathe tooling	141	1.2	3.0	70	3.4	5.9
polishing after grinding	186	3.5	3.0	71	3.2	5.8
rolling	36	1.2	2.0	10	1.2	1.6
milling process	110	2.0	2.4	51	1.0	2.8

Through a detailed X-ray analysis of the surface layers after heating (sintering), recrystallization was indicated up to depth 4 - 5 μ; up to the depth 15 μ appear some traces from the previous deformation.

Operational Characteristics of the Hardened Surface Layer.

Besides its own internal stresses, which can be harmful when combined with the operational stress, the varied character of the surface layers and that of the blade core increases the heat-diffusion rate at operational temperatures. This leads also to the loss of refractory elements Cr, Ti, Al from the surface layers. The characteristic results of (spectometrical) analysis were obtained after a specific time of operation from (etched) surface layers of the samples and these are presented in Figure 4. (Ref. 3).

The recrystallisation process occurs already in the first hours of operation in the mechanically hardened surface layer. Fine granular structure is developing, with lower hardness characteristics than the core, as well as having a lower lattice parameter. Fig. 5 shows the lattice parameters of surface layers of the blades manufactured from the alloy EI 437 A as depending on the length of operation (ref. 3). Beneath the recrystallized layer, which reaches up to a linear depth of only 3-5μ, follows a layer which, on the contrary has an increased lattice parameter, and is 7-9μ in depth;for the core of the blade itself are noted the values of the lattice parameter in depth of 50μ. The diminishing lattice parameters of the solid solution of Ni - Cr in the course of extended use is explained by diffusion of refractory elements into the oxydized layer.

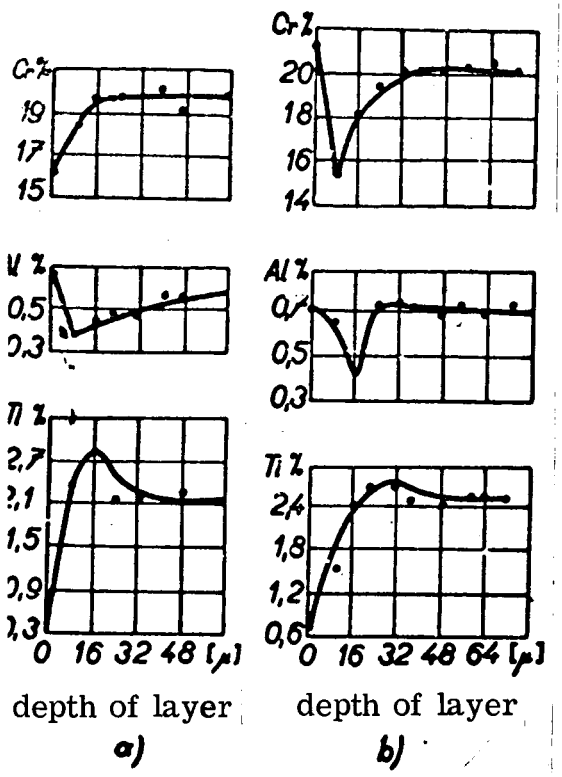

Figure 4. The Content of Chrome, Titan, and Aluminum in the Surface Layers of the Blades

a) duration of service 600 hrs. b) 1100 hrs.

The average composition of the outcoming alloy EI 437
Cr 19.5%; Ti 2.2 - 2.7%; Al 0.55 - 0.7%

Comparative Measurements for the Alloy EI 617

Up to now, the measuring has been done generally with the alloy EI 437. From some of the measurements introduced in the Soviet literature (ref. 4) it is evident that the alloy EI 617 will be governed by similar laws. The alloy EI 617 is even more suitable for mechanical hardening of the surface by finishing processes than the alloy EI 437. By comparing the samples of EI 437 and EI 617 which were processed under the same conditions it was found, that the depth of the hardened surface layer was on the average 20% higher in the case of alloy EI 617.

In VZLU we have conducted in cooperation with VZU Oll an X-ray analysis of lattice parameters of the surface layers of turbine blades which were manufactured from the alloy EI 617. The method of reflection with a registration on a flat film was used. The suitable lines for the measurements were obtained by using the illumination CU (reflecting level /420/ → angle σ = 78°22,2). Blades for the illumination were chosen from each stage of manufacturing. The measurements were taken on the trailing edge. Assuming that after the final heating (sintering) in argon the internal stresses caused by surface oil are removed, it is possible, by comparing the lattice parameters, to determine the amount of both main factors of stress that remain after each manufacturing process.

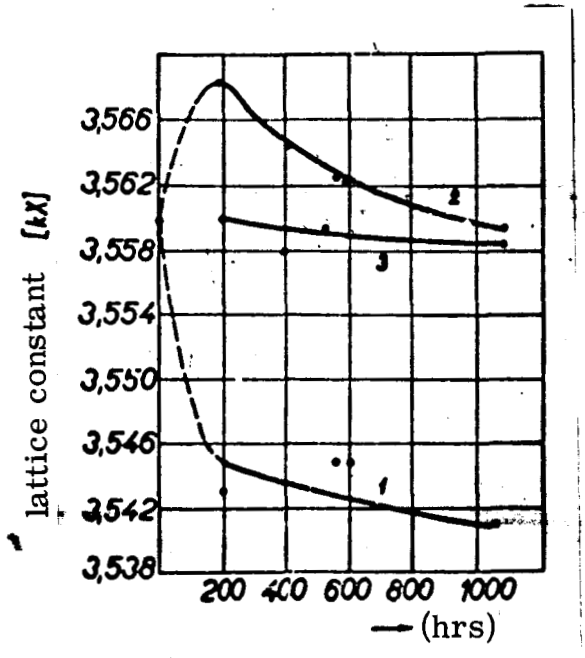

Figure 5. The Dependance of the Lattice Constant of the Solid Solution Ni -CR of the Surface Layer of the Blade on the Time Running.

1. recrystallized layer
2. substrate
3. the core of the blade

$$\sigma_1 + \sigma_2 = -\frac{E}{\nu} \cdot \frac{a - a_o}{a_o} \qquad (kp/mm^2)$$

σ_1, σ_2, - the main components of stresses (kp/mm^2)

E - flexual modulus

υ - Poisson ratio

a - measured lattice constant

a_o - lattice constant in a non tensile state (the value measure on the blades after heating (sintering)).

Even if - in regard to the specification of X-ray analysis - one cannot consider the values of stresses to be absolute (the precision of evaluating the stresses I 25 kg/mm^2), the results of the measuring show clearly the effect of each operation on the residual stress in the surface layer.

The results of the measuring are noted in table 5.

TABLE 5

Description of the Last Operation	a The Lattice Constant /A/	$\sigma_1 + \sigma_2$ (kp/mm^2)
cast	3.5739	= 38
scoop of block and rim roughly tooled	3.5708	+ 24
scoop refined	3.5725	- 10
scoop and rim abraded and polished	3.5766	- 92
dipping for controlling the macro-structure	3.5770	- 100
cutting off the technological waste	3.5764	- 88
final heating (sintering) in argon	3.5720	0

Conclusion /49

The heat-resistant alloys of the nickel base have the tendency for mechanical hardening of the surface layers as a consequence of surface machining.

The depth and degree of hardening depend on the method of machining used and vacillates evenly from 40 - 50μ after polishing, and up to 200 μ after lathe tooling. Due to hardening, the lattice parameters of the basic solid solution Ni -Cr change, which consequently causes development of immense internal stresses. By studying the dependence of various methods of machining on the long-lasting mechanical characteristics of heat-resistent alloys, the negative effect of hardening was proved, especially in the case of thermal fatigue. This effect is explained by a development of internal stress in the surface layer. Furthermore the difference in the character of surface layers from that of the blade core helps to increase the diffusion rate of the atoms at operating temperature. This leads towards loss of refractory elements in the surface and towards appearance of cracks.

These facts show the importance of a search for an optimal technological process of manufacture of turbine blades, which would lower the depth of the deformation of the hardened surface layer. In todays manufacturing processes the final operation is heating (sintering) in argon at 950°C. This is designed to remove the internal stresses which developed during the previous mechanical processes. Through the tests it was proven that such heating (sintering) does indeed remove the internal stresses. However, also was noted the recrystallization, up to the depth of 5μ, and up to the depth of 20 μ the traces of plastic deformation were found. It would be advisable to exploit the use of electrolytical polishing as the final operation in the manufacture of turbine blades for the complete removal of the deformed surface layer of blades.

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